STUDIES FOR STUDENTS.

DISTINCT GLACIAL EPOCHS, AND THE CRITERIA FOR THEIR RECOGNITION.[1]

I. INTRODUCTION.

IT has long been evident that writers on glacial geology are not at one concerning some of the important questions which underlie the interpretation of the history of the glacial period. Certain recent publications have served to emphasize the differences between them. There are two questions, at least, concerning which there must be agreement, or at any rate a common understanding, before existing differences can be eliminated or justly evaluated. When the answers to these questions have been agreed upon, or when the positions of the contending parties are clearly understood, it may be found that some of the apparent antagonisms have no better basis than differences in definition. Stated interrogatively, the two questions referred to are these: 1. What constitutes a glacial epoch as distinct from other glacial epochs? and 2. What are the criteria for the recognition of distinct glacial epochs, if such there were?

II. THE IDEA OF A GLACIAL EPOCH.

It is conceivable that, after the development and extension of a continental ice-sheet, it might be wholly wasted away. The maximum extension of such an ice-sheet would mark the culmination of a glacial epoch. If subsequently another ice-sheet of considerable dimensions were accumulated, its development and extension would constitute a second glacial epoch. These successive ice-sheets might be so related to each other in

[1] Read before the American Geological Society at Ottawa, Dec., 1892.

time, in position, and in the sequence of geological events, as to be regarded as separate epochs of the same glacial period.[1] On the other hand they might be so widely separated from each other in time, in position, and in the sequence of geological events, as to make their reference to separate glacial periods more appropriate. In any case their separation would be sufficiently marked to necessitate their reference to separate ice epochs. So far we believe there would be no disagreement.

If, instead of entirely disappearing, the first ice-sheet suffered great reduction of volume and area, and if this reduction were followed by a second great expansion of the ice, might the time of such expansion be regarded as a second glacial epoch of the common glacial period? To this question, too, as thus stated, we apprehend there would be but one answer, and that affirmative.

It seems certain that the edge of the continental ice-sheet was subject to more or less extensive oscillations, as are the ends of glaciers and the edges of ice-sheets to-day. How much of an oscillation is necessary, and under what attendant conditions must it take place, in order that the recession of the ice-edge shall mark an interglacial and its readvance a distinct glacial epoch? When the question takes this specific form, and when inquiry is made concerning the quantitative value of the different elements entering into the problem, we reach the battled ground. It is the battled ground, partly because it is the ground of misunderstanding. It is the ground of misunderstanding, partly because glacialists are not agreed as to the meaning of certain terms in common use by them.

Four elements seem to enter into the idea of an ice epoch as distinct from other ice epochs. These are (1) the distance to which the ice retreated between successive advances; (2) the duration of the retreat, or the time which elapsed between successive ice extensions; (3) the temperature of the region freed from ice during the time between maxima of advance; and (4)

[1] The terms period and epoch are here used in the sense in which they have been used most commonly in the literature of glacial geology in the United States.

the intervention between successive advances, of changes interrupting the continuity of geological processes.

(1) It would be arbitrary to name any definite distance to which the ice must recede in order to constitute its re-advance a distinct ice epoch. It would be not so much a question of miles as a question of proportions. Considering this point alone, we presume it would be agreed that an ice-sheet should have suffered the loss of a very considerable proportion of its mass, and that it should have dwindled to proportions very much less than those subsequently attained, before its re-advance could properly be called a separate glacial epoch. To be specific, if the North American ice-sheet, after its maximum extension, retreated so far as to free the whole of the United States from ice, we should be inclined to regard a re-advance as marking a distinct ice epoch of the same glacial period, if in such re-advance the ice reached an extension comparable with that of the earlier ice-sheet. Especially should we be inclined to refer the second ice advance to a second glacial epoch, if it, as well as the preceding retreat, were accompanied by favoring phases of some or all the other three elements entering into the notion of a glacial epoch. In this statement we do not overlook the fact that a northerly region—as Labrador or Greenland—might be continuously covered with ice throughout the time of the two glaciations of the more southerly regions. But this is not regarded as a sufficient reason for discarding the notion of duality. Greenland has very likely been experiencing continuous glaciation since a time antedating that of our first glacial deposits. The renewal today of glaciation comparable in extent to that of the glacial period would certainly be regarded as a distinct glacial epoch, if not a distinct glacial period, even though Greenland's glaciation may not have been interrupted. Scandinavia and Switzerland have probably not been freed from ice since the glacial period. Their snow and ice fields are probably the direct descendants of the ice fields of the glacial period. An expansion of the existing bodies of ice in these countries to their former dimensions, would constitute a new glacial epoch, if not a new glacial period.

Analogous subdivisions in pre-Pleistocene formations have been frequently recognized.

(2) The application of the time element is hardly susceptible of quantitative statement. We are inclined to think that it would be generally agreed that, with a given amount of recession of the ice, its re-advance would be more properly regarded as a distinct glacial epoch if the interval which had elapsed since the first advance were long. Whether a longer time between the separate advances might reduce the amount of recession necessary in order to constitute the second advance a second epoch, we are not prepared to assert; but we are inclined to think it might.

(3) The third element is perhaps somewhat more tangible than the second. If, during the retreat of the ice, the climate of a region which was twice glaciated became as temperate as that of the present day in the same locality, we should be inclined to regard the preceding and succeeding glaciations as distinct ice epochs, especially if the intervening recession were great and its duration long.

Unfortunately for simplicity and ease of determination, there are difficulties in determining with precision how far the ice retreated between successive maxima of advance, how long the interval during which it remained in retreat, and the extent to which the climate was ameliorated, as compared with that which went before and that which followed.

(4) If changes of any sort which interrupt the continuity of geological processes intervened between successive maxima of advance of the ice, the separation of the later advance from the earlier as a distinct ice epoch, would be favored. How great the intervening changes should be in order to constitute the re-advance a distinct ice epoch, is a point concerning which there might be difference of opinion. But it is altogether possible that such changes might intervene as alone to give sufficient basis for the separation Orographic movements, resulting either in continental changes of altitude or attitude are among the events which might come in to separate one ice

epoch from another. Changes of this sort have often furnished the basis for the major and minor divisions of time in other parts of geological history, so that there can be no question as to their adequacy, if they were of sufficient magnitude. We hold that the intervention of orographic or other important geologic changes might reduce to a minimum the amount of recession, the duration of the recession, and the warmth of the intervening climate necessary to constitute the separate ice advances separate ice epochs. The absence of great orographic or other changes in glaciated regions between successive advances of the ice would be no proof that such advances should not be regarded as separate epochs. Divisions of equal importance have often been made without evidence of such changes.

From the foregoing discussion, brief as it is, it will be seen that within certain narrow limits the definition of a glacial epoch, as distinct from other glacial epochs, must be more or less arbitrary. It is less important that an arbitrary definition should be accepted, than that the same meaning should be attached to technical terms in common use among geologists. In the interest of harmony and of a common understanding, and without the violation of any truth of science, we believe it would be well if the conception of a glacial epoch, as framed by those who are our leaders in position and in fact, were made the basis for our usage of the term.

III. The Criteria of Distinct Glacial Epochs.

If there have been differences of opinion concerning the nature of ice epochs, as distinct from each other and from ice periods, there has been a failure to adequately apprehend the nature, the extent, and the meaning of the real criteria on which the final recognition of separate ice epochs, if such there were, must be based.

Such criteria are several in number. They are of unequal value. In some instances a single one of them might be quite sufficient to establish the fact of two ice epochs. In other cases, single criteria which might not be in themselves demonstrative,

have great corroborative weight, when found in association with others. In all cases, much discretion must be used in the interpretation of these criteria. They may be enumerated under several specific heads.

(1) *Forest Beds.* Beds of vegetal deposits or old soils are frequently found between layers of glacial drift. This is one of the criteria most commonly cited, because it is of common occurrence and easy of recognition. The advocates of the unity of the glacial period maintain that such beds of organic matter might become interbedded with morainic debris during minor oscillations of the ice's edge. The phenomena of existing glaciers make it evident that forest beds or soils might be enclosed by the deposits of an oscillating ice edge. By repeated oscillations of the ice's edge during the general retreat of the ice, such vegetal beds might become interstratified with glacial drift more or less frequently over all the area once covered by the ice, and from which it has now disappeared. The mere presence of vegetable material between beds of drift is therefore no proof of distinct ice epochs. This does not destroy the value of the vegetal beds as a criterion for the recognition of distinct ice epochs, but it makes caution necessary in its application. It does not follow that, since *some* inter-drift forest-beds do not prove interglacial epochs, *none* do. The question is not how forest-beds might originate, but how existing forest-beds did originate.

Where the plant-remains found in the relations indicated are so well preserved as to make identification of the species possible, we have a means of determining, with some degree of accuracy, the climatic conditions which must have obtained at the place where the plants grew during the time of their life. If these interbedded plant-remains are of such a character as to indicate a temperate climate, we can not suppose that they grew at the immediate edge of the ice, and therefore that they were buried beneath its oscillating margin. To be specific, if the inter-drift plant remains in any given locality of the area once covered by ice are such as to indicate a climate *as warm as the present in the same locality*, the ice must have receded so far to

the northward that its re-advance might, in our judgment, appropriately be regarded as a separate ice epoch.

It has been suggested in opposition that temperate conditions may obtain even up to the edge of the ice, and that interbedded vegetal remains indicating temperate climate do not prove any considerable recession of the ice. The phenomena about existing glaciers have been appealed to in support of this demurrer. But the objection is not well taken. The climatic conditions which obtain about the borders of small, local glaciers, are not a safe guide as to climatic conditions which obtained about the margin of a continental ice-sheet, any more than the climatic conditions which obtain about a small inland lake are a safe criterion as to the climatic conditions about a sea-coast. The general principles of climatology, as well as specific facts concerning plant distribution, seem to us to indicate that the climate about the border of a continental ice-sheet must have been arctic.

It is evident that the greater the distance north of the overlying drift remains of temperate plants are found, the more conclusive becomes the evidence. Plant remains indicating temperate climate at the very margin of the drift sheet which overlies them, would be less conclusive than similar evidences one hundred miles to the northward. It might be difficult to prove in any given instance that the ice which deposited the drift overlying plant remains advanced one hundred miles, or any other specific distance, south of any particular underlying forest bed. If the forest bed were continuous for the whole distance, the case would be clear. It would also be conclusive if the continuity of the drift overlying a forest bed at any point with that of a remote point to the south, could be demonstrated. In spite of these difficulties in its application, the vegetal beds constitute a valuable criterion in making the discriminations under consideration, when they are properly applied. Under proper circumstances the criterion may be conclusive when taken alone, and it may have corroborative significance when not itself conclusive.

The absence of forest beds and of all traces of vegetal deposits whatsoever between beds of drift, is no proof of the absence of

recurrent ice epochs, since the second advance of the ice might have destroyed all trace of the preëxistent soil and its vegetal life. It is always possible, too, that such beds exist, even if they have not been discovered. It would have been anticipated that they would not be abundant, or wide spread. The absence of forest beds is therefore at best no more than negative evidence.

(2) *Remains of Land Animals.* Bones of mammalia or remains of other land animals, occurring in relations similar to those in which forest beds occur, may have a like significance. Their value as a criterion of separate glacial epochs is subject to essentially the same limitations as forest beds.

(3) *Inorganic Products formed during a time of Ice Recession.* The recession of the ice after a maximum of advance would leave a land surface more or less affected with marshes and ponds. In such situations bog iron ore might accumulate, if conditions were favorable. Such ore beds, buried by the drift of a later ice advance, would have a significance comparable to that of forest beds, except that they would give less definite information as to climate, and would be correspondingly less trustworthy. Should such ore beds be found in such relations as to prove that the underlying and overlying bodies of drift were deposited by ice sheets which extended great distances further south, their significance would be enhanced. From the thickness of the ore beds some inference might be drawn as to the length of time concerned in their accumulation. But because of the variable rate at which bog ore may accumulate, such inference should be used with caution.

Concretions of iron oxide might be formed in the marshes or in ill-drained drift areas where accumulations of greater extent were not made. A subsequent incursion of the ice might incorporate these nodules with its drift, wearing and striating them as other stones, and depositing them as constituent parts of the later drift. Such iron nodules in the later drift would mean a recession and re-advance of the ice with some considerable interval between, although not necessarily an interval sufficiently

warm or long to be regarded as an interglacial epoch.[1] Calcareous concretions, like those of the loess, would possess a like significance, in like relations. While in themselves these inorganic products of a time of ice recession might fail to be conclusive of separate ice epochs, they might have much corroborative significance when associated with other phenomena. An inter-till iron ore bed, associated with a forest bed which indicated a warm climate would be most significant.

The absence of knowledge of ore beds between sheets of till, and the absence from an upper bed of till of concretions of iron and lime carbonate formed during a recession of the ice, would be no proof that interglacial epochs did not occur. These products were probably formed in relatively few localities. They stood good chance of destruction at the hands of the returning ice, and they may exist, where they have not been discovered, or where their significance has not been understood. Their absence is at best no more than negative evidence.

(4) *Beds of Marine and Lacustrine Origin.* If between beds of glacial drift there be found beds of lacustrine or of marine origin, such beds would indicate a recession of the ice during their time of deposition. Their position would be a minimum measure of ice recession. If such lacustrine beds contain organic remains, they will bear testimony concerning the climatic conditions which existed where they occur, at the time of their deposition. If the fossils in such beds denote a temperate climate, or a climate as mild as that of the present day in the same region, the ice must have receded so far to the northward as, in our judgment, to constitute its re-advance a distinct ice epoch. This line of argument may be even stronger than that drawn from remains of terrestrial life, since the ice would probably affect the temperature of the sea to greater distances than that of the land, and affect it to a greater degree within a given distance. The argument becomes stronger the further north the inter-drift marine and lacustrine deposits occur, since the ice must always

[1] This point concerning iron nodules was suggested to the writer by Mr. W. J. McGee.

have receded to a position still further north. If marine or lacustrine beds lying far north of the later ice limit contain proof of temperate climate, the argument becomes conclusive.

The absence of marine and lacustrine deposits between beds of drift, would be no proof that interglacial epochs did not occur. Lacustrine beds could be made only where there were lakes, and lakes would be the exception rather than the rule. Marine beds in similar positions would rarely be known, except where a definite succession of changes of level has taken place. Both classes of deposits, if once formed, would be subject to destruction by the over-riding ice of a later epoch, if such there were. Neither would be likely to be preserved at all points where formed, and both may exist at many points where their existence is not known. The absence of these beds is at best no more than negative evidence.

(5) *Beds of Subaërial Gravel, Sand and Silt.* Layers of stratified drift between layers of ground moraine, are of common occurrence in many regions. Under ordinary conditions their existence is not regarded as evidence that the underlying and overlying tills are to be referred to separate ice epochs. But it is conceivable that beds of stratified drift may, under the proper circumstances and relations, be strong evidence of separate ice epochs. The last stages of ice work in the glacial period were accompanied, in many regions, by the deposition upon adjacent land surfaces, of extensive bodies of gravel and sand, washed on beyond the ice by waters issuing from it. Except in valleys through which strong currents coursed such deposits were apparently not carried far beyond the edge of the ice. But as the edge of the ice withdrew to the northward, sand plains may have extended themselves in the same direction, by additions to their ice-ward faces. It is conceivable that the process of subaërial plain building at the edge of a receding phase of ice might be carried so far under favorable circumstances, as to result in the construction of plains of great extent. In this event, a subsequent ice-advance might overspread such plains in such wise as to bury, without destroying them, though such a course of

events would certainly be exceptional. In order to constitute the inter-stratified gravel and sand evidence of separate ice-epochs, its continuity for great distances between beds of till, and in the direction of ice movement, would need to be demonstrated. In themselves, these beds, under the conditions indicated, would simply be a minimum measure of the amount of ice recession between the deposition of the underlying and overlying bodies of till. It is hardly likely, though possible, that the continuity of inter-bedded gravel and sand could be proved for a sufficient distance north of the southern limit of the less extensive bed of ground moraine, to alone constitute evidence of a recession of ice great enough to make it necessary to refer its re-advance to a new epoch. Beds of silt in like relations, deposited by waters beyond the edge of the ice, would have a like significance so far as the question here under consideration is concerned. Such beds of stratified drift might sometimes have corroborative value when their testimony, taken by itself, is inconclusive. If, for example, their surfaces are marked by forest beds, and especially by forest beds whose plants denote a warm climate, the association becomes most significant.

In view of what has been said, it is evident that the absence of beds of subaërially stratified silt, sand, and gravel, between beds of till can not be brought in evidence against separate ice epochs. It would rarely be true that topographic and hydrographic conditions would make possible the construction of plains of sufficient extent to serve as criteria for the purpose here indicated, and a few of those formed would escape such a degree of destruction as to leave them demonstrably continuous. There is also the further possibility that such beds exist, even though their continuity be not known. To prove the continuity of a buried bed of stratified and incoherent drift, even if it existed, would be a most difficult task.

(6) *Differential Weathering.* If, after covering a given region, the ice retreated, the drift which it left in the area which it previously covered would be subject to oxidation, leaching and disintegration. The depth to which this oxidation, leaching

and disintegration would extend, would be dependent upon the length of time during which the drift was exposed, and upon the climate which affected the region during its exposure. The longer the exposure and the warmer the climate, the deeper would the weathering extend. If, subsequently, the ice extended over the same region, it might, in some places, override and bury the old surface without destroying it. The earlier oxidized and leached drift would thus come to be buried by the newer unoxidized, unleached drift. If, therefore, beneath the newer drift of any given locality there be found a lower drift, the surface of which is oxidized and leached to a considerable depth, the evidence is strong that the lower drift was exposed for a long period of time before the upper drift was deposited upon it. Within certain limits a similar result might be brought about, it is true, if the ice, after having reached a certain maximum stage of advance, were to retreat for a short distance only and there remain for a very long period of time. A subsequent minor advance might bury the oxidized surface of the drift beyond the position of the long ice-halt. Under these conditions, the climate which would have obtained in the area of the drift exposed during the minor retreat would have been cold, and oxidation, leaching, and disintegration would have proceeded slowly. If they reached considerable depths, the time involved must have been very long. If this surface of oxidized and leached and disintegrated drift were found to reach far to the northward beneath the layer of newer and upper drift, it would indicate a great recession of the ice. We maintain that if it were found sufficiently far north of the margin of the overlying drift, and if its depth were sufficiently great, extending well down below any possible accumulation of superglacial till, it might be a positive criterion of so great a recession of the ice, protracted through so great an interval of time, as to constitute its new advance a separate ice epoch.

There is much reason to believe that the soil developed under the influence of a warm climate differs in some respects from one developed from similar material under other conditions. The well-known fact that red and reddish soils are especially

characteristic of low latitudes and warm climates is significant. If therefore a soil developed on the surface of one sheet of drift and buried by another, be found to possess, in addition to unmistakable marks of long exposure, the peculiar marks which seem to be characteristic of soils developed under high temperatures, the argument gains in strength.

This argument from oxidation and weathering has another application. If in a later advance, following a protracted recession, the ice-sheet failed to reach the limit of its earlier advance, there would remain an area of drift deposited by the first ice-sheet, outside the drift deposited by the later. Now if the time interval between these two advances was great, and especially if during this interval the climate was mild, the oxidation and weathering of the older drift surface would be markedly different in degree from that of the newer. If, under these circumstances, the surface of the older sheet were found to be weathered and oxidized and reddened up to the border of the newer drift sheet, and if here there were found to be a sudden change in the character of the surface of the drift so far as depth and degree of oxidation and weathering is concerned, we should have strong evidence that the one sheet of drift was much older than the other. The statement sometimes urged that the drift which was deposited near the edge of the greatest ice advance would be largely made up of the residual materials which occupied the surface invaded by the ice, would not meet the case. For if it be granted that this statement is qualitatively good, we should find the greatest degree of weathering and oxidation at the extreme margin of the drift, and should be found to be less and less on receding from this margin. There would in this case be no sudden transition from a deeply weathered and oxidized surface, to one which is fresh and unoxidized, along a definite line. We maintain that if the whole of the drift deposits are referable to one epoch, there should be no sudden transition in the surface of the drift from that which is deeply weathered to that which is not, the one surface being separated from the other by a definite and readily traceable line.

It has been urged against the criterion of differential weathering that superglacial material is or may be thoroughly oxidized before its deposition, and that a layer of oxidized drift between layers of till may be no more than superglacial debris deposited during a minor recession of the ice.[1] We believe that this attempt to eliminate the value of this criterion rests partly on an exaggerated idea concerning the amount of superglacial material, but more especially on a failure to apprehend the real meaning of the argument for the validity of the criterion, and upon a failure to note the limitations imposed upon it by its advocates. It is not affirmed that a layer of oxidized drift between beds of unoxidized drift is *per se* proof of two glacial epochs; but it is affirmed that if such layer of weathered drift can be shown to extend far below any possible superglacial till, into the subglacial till below, in such wise as to indicate that it is the result of subaërial exposure in a warm climate subsequent to its deposition and prior to the deposition of the overlying till, it constitutes the best possible evidence of an interglacial epoch, especially when accompanied by the corroborative testimony of other criteria. It is further affirmed that if the second sheet of drift failed to reach the limit of the first, and if the drift which was deposited by the first and never covered by the second ice-sheet, is more thoroughly and more deeply weathered than that deposited by the second, and especially if the two types of drift surface meet along a definite and readily traceable line, the argument becomes, in our judgment, irrefragable. In its application, this criterion would be infallible only in the hands of one who could distinguish between superglacial and superglacially oxidized material on the one hand, and material subaërially weathered after its deposition, on the other.

In circumstances and relations where the weathering of the drift is not in itself conclusive, it might still have corroborative value in association with other lines of evidence.

The absence of an oxidized and disintegrated zone of drift

[1] This point was urged at the reading of the paper at Ottawa, by Prof. C. H. Hitchcock, Mr. Upham, and others.

below a superficial layer which is not oxidized, would be no proof that there were not distinct ice epochs, since the ice of any later epoch, if such there were, might have planed off the surface of the drift left by its predecessor to the depth of the weathering. The preservation of such surfaces after a second ice invasion must be regarded as the exception rather than as the rule. There is always the possibility, too, that an oxidized and weathered zone marking the surface of an older drift sheet exists, where excavations have not opened full sections of drift to view. The absence of weathered zones of drift beneath the surface, or the absence of knowledge of their existence, is therefore at best no more than negative evidence. The absence of greater weathering of the drift outside the limit of the drift supposed to belong to a later epoch, would be positive evidence against the reference of the two sheets of drift concerned to different epochs.

A specific part of the above line of evidence may be separately mentioned. One phase of weathering is the disintegration of boulders, and this is a point which can be readily applied even by those who are not geologists. If the boulders of one region are much more commonly disintegrated than those of another, and if the two regions are separated from each other by a well-marked boundary line, the inference lies close at hand that the boulders in the one case have been much longer exposed to disintegrating agencies than in the other. It is no answer to this argument to say that the materials lying at the very front of the drift deposits contain boulders which were derived from the disintegrated rock over which the ice has passed, and that they were therefore in a less firm state at the outset. In many cases these boulders have come from great distances, and coming from great distances they must have come in a firm and solid state, else they could not have suffered such extensive transportation, except indeed their position was superglacial throughout their whole journey. This argument has equal force when applied to the area covered by the two sheets of drift where two exist. If within the region of drift under investiga-

tion we find a surface layer of greater or less depth, the boulders of which are hard and fresh, and if beneath this we find another layer of drift, the stony material of which is largely disintegrated, at least in its upper parts, we have good evidence that the surface bearing the disintegrated boulders was exposed for a considerable length of time before the deposition of the overlying drift, which carries fresh boulders. Since the disintegration of boulders is only one phase of weathering, the limitations of this argument are identical with those already noted in connection with the general argument from differential weathering.

(7) *Differential Subaërial Erosion.* If the drift deposited by one ice-sheet were to be exposed for a considerable interval of time, and if the ice in its subsequent advance failed to reach the limit of its first invasion, the two areas should show different amounts of subaërial erosion, since the one has been exposed to the action of air and water much longer than the other. The line which marks the limit of the later ice invasion should be the line of more or less sudden transition from an area without, where stream erosion has been greater, to an area within, where stream erosion has been less.

The point here made can not be met by the suggestion that the greater erosion of the outer area was effected by the water issuing from the ice which had retreated to the position now marked by the border of the area of the lesser erosion. So far as we know, such waters would be depositing, not eroding. Furthermore, much of the erosion of the outer area would have such relation to drainage lines that waters issuing from the ice could never have reached the localities where it is shown.

If the outer and older drift be found to have suffered ten times as much stream erosion as the inner and newer, it is fair to assume that it has been exposed something like ten times as long, if the conditions for erosion are equally favorable in the two regions. The argument has especial weight if it can be found that beneath the newer drift the surface of the older is such as to indicate that it was deeply eroded before the newer

was placed upon it. The argument is stronger the farther from the margin of the newer drift such erosion on the surface of the underlying older drift can be proved to have taken place. In other words, if, in addition to the greater surface erosion of the older drift sheet as now exposed outside the limit of the newer drift, we find a notable unconformity between the newer and the older drift, and especially if this unconformity lie far enough north of the margin of the newer drift, the argument becomes conclusive.

When differential erosion and drift unconformities are not in themselves conclusive, they may have great corroborative value in conjunction with differential weathering, forest beds, or other indications of separate ice epochs.

The absence of observable unconformity between sheets of drift would be no proof that there were not distinct and widely separated ice epochs, since the later ice invasion might have so far modified the surface which it transgressed, as to destroy all patent evidences of unconformity. It would have been anticipated that distinct unconformities in the drift would be rare, even if there were distinct ice epochs, for the same reason that weathered zones and forest beds would be rare. But if the drift which lies outside a line supposed to mark the limit of a sheet of drift belonging to a later ice epoch, be not more eroded than that which lies within such line, the absence of greater erosion in the outer drift is positive evidence against the reference of the drift of the two areas to distinct ice epochs, if conditions for erosion in the two areas are equally favorable.

(8) *Valleys Excavated Between Successive Depositions of Drift.* A closely related, but not identical, point may be found in the extent of the valley excavations which can be proved to have taken place between the deposition of the earlier and later drift. We do not refer to valleys excavated in the drift especially, but to those excavated in other formations as well. If it can be shown, for example, that after the deposition of an earlier drift sheet, and before the deposition of a later, valleys were excavated which extended not merely into the drift itself, but far

beneath the drift into the underlying rock, these valleys would be conclusive evidence of a long interval between the deposition of the two bodies of drift. The argument is of especial force when such excavations in the rock beneath the drift can be shown to have taken place at great distances within the margin of the newer drift. For valleys in such situations imply that the ice had receded at least as far to the north as they lie, during the interval between the two drift depositions, and may be so situated as to show that the ice had wholly left the drainage basin where they occur.

The absence of evidences of deep valley excavations in any given region during a supposed interglacial epoch, is no proof that such interval did not exist. The conditions may not have been everywhere favorable for erosion within the limits of any narrowly circumscribed area, and the absence of interglacial valleys would be only negative evidence against an interglacial epoch. The absence of such evidence everywhere would bear against the existence of an interglacial epoch of much duration in such wise as to be more than negative evidence.

(9) *Different Directions of Movement.* If, after its maximum advance, the ice suffered merely a minor recession and then remained stationary, or nearly so, for a time, the general direction of its movement in a subsequent advance would probably be essentially the same as in the earlier. But if, after its maximum advance, the ice receded to a great distance, and especially if it entirely disappeared, a subsequent ice-sheet might have a very different direction of movement, since its center of accumulation and dispersion might be very different. It is conceivable that this center might shift during the history of a single ice-sheet. In this case there should be a gradual change in the direction of ice movement, not an abrupt one. If, therefore, there be found one sheet of drift made by an ice movement in one direction, overlaid by another sheet of drift deposited by ice moving in a very different direction, with an abrupt transition between them, such drift sheets would be presumptive evidence of distinct ice epochs. An exception would need to

be made in the case of drift sheets along the margins of confluent or proximate ice lobes. In such cases, if the one lobe temporarily secured the advantage of the other, drift beds formed by movements from opposite directions might be found in vertical succession, without being evidence of separate ice epochs.

It is no part of the purpose of this essay to point out the difficulties which might arise in the application of this criterion of diverse directions of ice movements. It is possible that gradual changes in the direction of movement might leave records which would seem to indicate abrupt changes instead. This possibility makes care necessary in the application of the criterion, but does not destroy its value. When not itself conclusive, this criterion may be so associated with differential weathering, differential erosion, forest beds, etc., that their combined testimony makes but one conclusion possible.

The absence of evidence of radically diverse directions of movement during the time of deposition of the various sheets of drift, would be no proof that there were not distinct epochs. In the first place, the movements of different epochs might be harmonious — a condition of things more probable than any other of the more common views of the causes of glaciation be correct. In the second place, if the movements were diverse, the deposits might still be so similar that their differentiation, when the one is buried, might not be easily made. In the third place, the later ice might have so far incorporated the older drift material with that which belonged more properly to it, as to have destroyed all definition between them.

(10) *The Superposition of Beds of Till of Different Physical Constitution.* After the retreat of an ice-sheet, the surface of the country thus discovered would be largely mantled with drift. This drift would serve to protect the underlying rock from disintegration. But where there was little or no drift, the rock surface would be subject to all the disrupting agencies which affect surface rocks. The same would be true of all rock surfaces bared by subaërial erosion after the disappearance of the ice.

Under these conditions, if a second sheet of ice invaded the region in question after it had been long exposed, it would find a surface prepared to yield large bowlders. The result would be the deposition of a new sheet of drift containing bowlders much larger than those which would have been proper to an ice-sheet overspreading a surface but recently abandoned. If, therefore, in the upper two layers of subglacial till, bowlders of great size preponderate, as compared with those of a lower homologous layer, they may be indicative of a great interval of time between the deposition of the upper and lower beds of drift. If the home of these bowlders be far north of the limit of the lesser sheet of drift, the distance, as well as the duration, of the ice retreat must have been great, and the reference of the two beds of till to distinct ice epochs would be favored. The case might be so strong as to make no other interpretation possible. Where in itself inconclusive, this criterion would have corroborative significance. In its application, the discrimination of subglacial and superglacial till would be imperative.

The absence of physical dissimilarity between superposed layers of subglacial till would not be proof of the absence of separate glacial epochs. The phenomena constituting the criterion could hardly be expected to be of common occurrence. They would never be obtrusive, and may easily have escaped attention where they exist.[1]

(11) *Varying Altitudes and Attitudes of the Land.* Another line of argument has to do with the altitude and attitude of the land during the deposition of various members of the drift complex. If during the deposition of one part of the drift that part of the continent covered by the outer part of the ice was low, the drainage from it would be sluggish. If the deposits of this drainage persist to the present time, we may find in their character evidence of the nature of the drainage, and therefore of the attitude of the land. If at a later time of drift deposition the glacial drainage in the same region was more vigorous,

[1] The 10th criterion, in the order here named, was suggested by Mr. McGee in the discussion which followed the reading of the paper at Ottawa.

the deposits made by the glacial streams would be correspondingly coarser. In these deposits, if they persist to the present day, we should find conclusive evidence of the swiftness of the streams. If it can be shown that during the deposition of one sheet of drift drainage was sluggish, and that during the deposition of a later body of drift the drainage was vigorous, these facts are evidence of an interval between the two times of drift deposition sufficiently long to accomplish the corresponding changes in elevation or attitude. Since such changes of altitude and attitude are generally believed to have been accomplished slowly, the interval must be believed to have been of considerable duration.

It is true that continental altitudes and attitudes might change during a single epoch of glaciation. If the change thus brought about resulted in increased slope, the more sluggish drainage of the earlier part of the epoch would be gradually transformed into the more vigorous drainage of the later part. In this case, if the evidence of both the earlier sluggish drainage and of the later vigorous drainage remain, there should also remain the evidence of the intermediate stages. If the deposits representing the intermediate condition of drainage do not exist, while those representing both extremes do, there would be the best of reason for believing that the intermediate phases of drainage did not exist during a glacial epoch, but during an interglacial epoch, when streams were not handling glacial debris, and when they were eroding rather than depositing. The deposits of the slow and of the swift drainage might occur in such relations as to prove, beyond peradventure, that intermediate stages of *glacial* drainage never existed.

If the sluggish drainage accompanied the maximum ice invasion, while the vigorous accompanied a lesser, the evidence of the swift streams might be found far north of the southern limit of the earlier drift. The farther north of the outer border of the older drift the gravel representing the vigorous drainage of the later and minor ice-sheet occurs, the further the ice must have retreated before the change from the one type of drainage

to the other was effected. On the other hand, the farther north of the limit of the later ice advance the sluggish drainage accompanying the earlier ice-sheet may be traced, the farther must the ice have receded before the changes resulting in vigorous drainage occurred. Under certain relations, the retreat of the ice might be shown to have been great enough, before the orographic movements which altered the nature of the drainage, to constitute in our judgment, a re-advance a distinct ice epoch. If for example throughout the course of a long river whose basin was largely covered with ice, there be evidence that sluggish drainage obtained during the maximum ice advance, and during all stages of the ice retreat until the basin was free from ice, and if there be evidence of a vigorous glacial drainage in the same valley at a later time, with no gradations between the two types, we have proof positive of at least a great recession, and of a considerable elevation of the land after the ice had receded beyond the limits of the drainage basin and before it again reached it in its re-advance. We hold that these phases of glacial drainage deposits may be so related to each other, to the valleys in which they occur, and to more or less distinct bodies of glacier drift, as to prove so great a recession of ice between the diverse phases of drainage deposition, as to constitute the second advance a distinct ice epoch.

The absence of evidence that the land stood at different elevations during different parts of the period of drift deposition, does not in any way militate against the theory of recurrent and distinct ice epochs. A constant attitude of the land is the thing to be assumed, until positive evidence to the contrary is adduced.

(12) *Vigor and Sluggishness of Ice Action.* If it can be shown that during one epoch of glaciation, we will say the epoch of maximum ice extension, the ice action was relatively sluggish, while during a later and minor advance its action was vigorous, the difference of action might be regarded as presumptive evidence of distinct ice epochs. Evidence of the two phases of ice action here referred to are difficult of definition, but they have been

independently noted by more than one glacialist. It is true that a forward oscillation of the ice edge might be more forceful than an earlier forward movement which might have reached a greater extension. In itself, therefore, this line of evidence can not be regarded as possessing great value.

It has been indicated that under certain circumstances, and in certain relations, some of the foregoing criteria, taken singly, may be conclusive of glaciations so distinct from each other, as to make their reference to separate epochs proper. But where the facts and relations which constitute one of the criteria are found, the facts and relations constituting one or more of the others are likely to be found as well. Where two of the foregoing criteria are found to be coexistent, their joint force is greater than that of either one. If neither one be absolutely conclusive, the two may still be, since the one may exactly meet the deficiency of the other. If three or more concurrent lines of evidence exist in any locality, the case is still further strengthened. We maintain that several of the foregoing criteria may be so related to each other and to the formations concerned, as not only to make the recognition of separate ice epochs proper, but to make the failure of such recognition altogether unscientific. Even when a single line of evidence, or when double, or triple, or quadruple lines of evidence are not absolutely conclusive in ruling out every conceivable technical escape from the conclusion that there were separate ice epochs, their cumulative and corroborative force may still be such as to carry conviction scarcely less positive than that which mathematical demonstration would afford. In the nature of the case not all of these various lines of evidence could be expected to be found in any one locality, or perhaps in any one limited geographic area, but where one occurs, some or all of the others are liable to be found under favoring circumstance. The number of criteria, and the great extent of area where they may hope for application, afford great possibilities.

From the foregoing discussion, it will be readily seen that the nature of the criteria and the limitations imposed upon their

application by the difficulty of proving stratigraphic continuity in such a formation as the drift, necessitate the greatest care in their use, and reduce the value of hasty and inexpert conclusions to a minimum.

IV. Areas Where the Criteria find Readiest Application.

The foregoing criteria find their readiest application in regions where a later sheet of drift, suspected of belonging to a later ice epoch, failed to reach the border of an earlier sheet of drift, suspected of belonging to an earlier ice epoch. The 1st, 2d, 3d, 4th, 5th and 10th as enumerated above, find their application wholly within the area affected by the drift of the separate epochs, if such there were. While within this general area they may be looked for at any point, they are likely to be of rare occurrence, except along a somewhat narrow belt, say 50 to 100 miles, adjacent to the border of the lesser ice advance. The conditions for their occurrence and detection are greatly favored if the lesser drift sheet be the later. The 6th, 7th, 9th and 12th criteria might hope for application within the same belt, but especially along a narrow zone on either side of the margin of the later drift sheet. It is along this zone that the types of surface are thrown into sharpest contrast, both as to material and topography. The 8th and 11th criteria have still wider limits of application, both within and without the border of the lesser ice advance.

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